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DETERMINATIONS OF THE HWW AND HZZ COUPLINGS AT THE LHC AND AT A LC.

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E Berger and John Campbell, hep-ph/0403194, ANL-HEP-PR-04-4

Introduction and Motivation

- Assume a SM-like Higgs boson has been discovered, $115 < m_H < 200$ GeV at the Tevatron or the LHC, and that a sample exists of $H + 2$ jet events at the LHC
- Want to use these data to determine the Higgs boson couplings g to weak vector bosons, W and Z
- Focus on two production subprocesses that contribute to $H + 2$ jet events:
  - $W + W \to H$ and $Z + Z \to H$ "WBF"
  - $g + g \to H$ "irreducible QCD background"
- Issue for the determination of couplings: How well can we resolve WBF production of H from QCD production of H?
- Independent calculation of $H + 2$ jet processes
  - to gauge the effectiveness of cuts used to select the WBF signal, and
  - to evaluate the accuracy with which coupling g can be determined in experiments at the CERN LHC

Introduction and Motivation (continued)

- Define Purity $P = \frac{S}{S+B}$

  S is the number of signal $H + 2$ jet events and

  B is the number of $H + 2$ jet QCD background events

  both in the WBF region of phase space

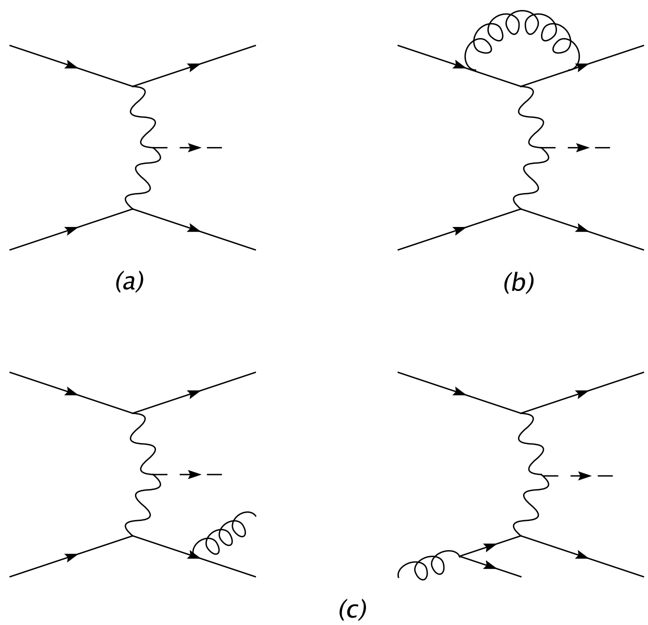
- Study Purity P of the signal vs p_T of the jets

- Evaluate uncertainty $\frac{\delta g}{g}$ of the coupling in terms of

  P $\frac{\delta N}{N}$ $\frac{\delta S}{S}$ and $\frac{\delta B}{B}$

$H + 2$ Jet Production – Signal

- Higgs boson H production via WW scattering in NLO QCD. Ex:



- QCD NLO calculation of $H + 2$ jets with CTEQ6M parton densities; renormalization/factorization scale $\mu = m_H$

- Hard perturbative scale μ dependence $\sim 2\%$ for $\frac{1}{2}m_H < \mu < 2m_H$, and CTEQ PDF uncertainty $\sim 3\%$, both in the WBF region of phase space
  $\rightarrow$ signal is calculated fairly reliably

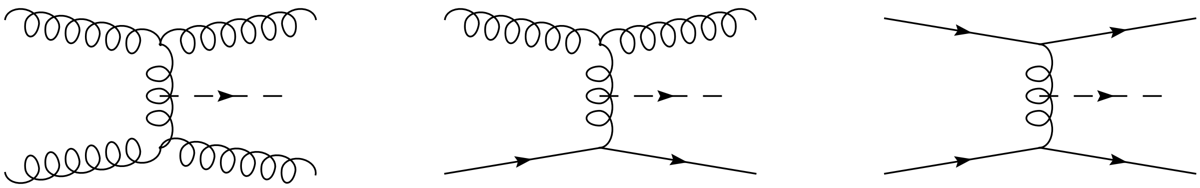
- Events generated with the MCFM code

  J. Campbell & R. K. Ellis PRD65,113007 (2002)

- Independent results (dipole subtraction method) verify the NLO calculation of Figy, Oleari, Zeppenfeld, PRD68, 073005 (2003). K-factor $\sim 10\%$, with small variation over the phase space appropriate for the WBF signal

$H + 2$ Jet Production – Irreducible Background

- Higgs boson H production via gg scattering. Ex:



- Fully differential NLO calculation of $H + 2$ jet production does not exist; contribution computed at LO Kauffman Desai and Risal, PRD55, 4005 (1997); PRD58, 119901 (1998)

- Effective ggH coupling included in the limit of $m_H \ll 2m_t$ and $p_T^H < m_t$

  (c.f. Del Duca et al NP B616, 367 (2001))

- NLO enhancement (K) factor is needed in the region of the WBF cuts. It can be estimated from
  - inclusive NLO $gg \to H$ $\quad K \sim 1.7 - 1.8$

    Harlander & Kilgore PRD64, 013015 (2001); Anastasiou & Melnikov, NP B646, 220 (2002)

  - NLO $gg \to H + 1$ jet $\quad K \sim 1.3 - 1.5$

    Ravindran, Smith, van Neerven NP B665, 325 (2003)

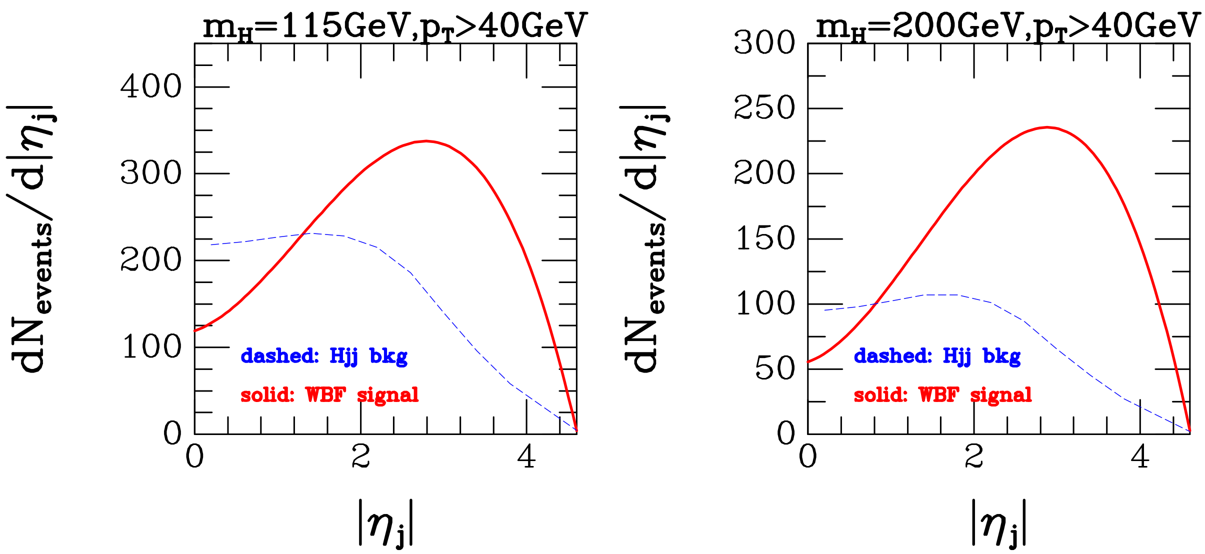
- Uncertainty: hard scale μ dependence ....

Event Characteristics

- Hallmark of WBF events in hadron reactions is a Higgs boson accompanied by two “tagging” jets having large $p_T \sim \mathcal{O}(\frac{1}{2} M_W)$
- QCD $gg \to H + 2$ jets generate a softer p_T spectrum
- The rapidity spectra for the WBF and QCD production mechanisms also differ, related to the fact that the gluon parton density (that plays a dominant role in the background) is softer than the quark density; figures shown on next slide
- The p_T spectrum of the Higgs boson is also relatively hard. All-orders resummed calculation Berger and Qiu PRD 67, 034026 (2003) provides $< p_T^H > \sim 35$ GeV at $m_H = M_Z$, growing to $< p_T^H > \sim 54$ GeV at $m_H = 200$ GeV
- Require reliable QCD representation of Hjj for jets at large p_T. Hard matrix elements are needed. A showering approach for generating the momentum distributions of the jets would not suffice; showering yields softer jets and overestimates signal purity

$H + 2$ Jet Production – Jet Rapidity Distribution

- Higgs boson H production via WW and ZZ scattering in NLO and via gg QCD processes (LO) (for 1 fb^{-1}, no BR included):



- Shape of the signal distribution depends very little on the Higgs boson mass or on the p_T cut for the tagging jets. Peak at $|\eta| \sim 3$. Full width at half-max ~ 2.8

- Background falls off sharply beyond $|\eta| \sim 2$

- Motivates a simple WBF prescription:

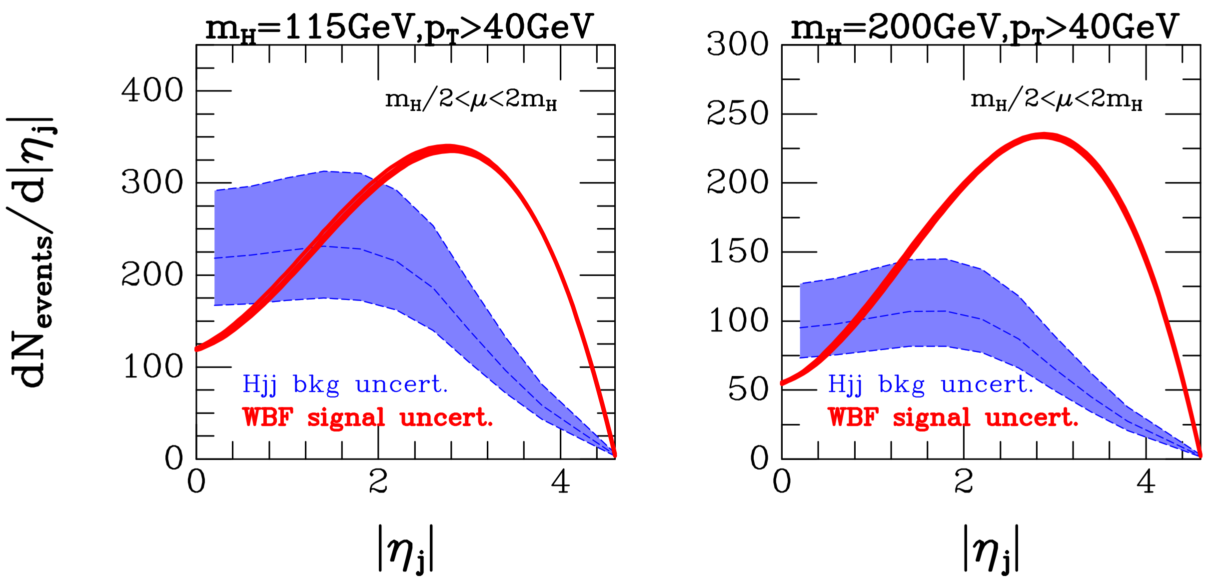
$$\eta_{\rm peak} - \eta_{\rm width}/2 < |\eta_j| < \eta_{\rm peak} + \eta_{\rm width}/2$$

$j = j_1$ or $j = j_2$, $\eta_{\rm peak}$=3, and $\eta_{\rm width}$=2.8

- This is our working definition of the WBF region

$H + 2$ Jet Production – μ dependence

- Higgs boson H production via WW scattering in NLO and via gg QCD processes (LO)
  hard-scale μ variation from $\mu = m_H/2$ to $\mu = 2m_H$:



- Magnitude and shape of the signal distribution depend very little on μ: $\pm 2\%$
- Magnitude of the background shows significant uncertainty at LO; it is 70% greater at $\mu = m_H/2$, and 40% less at $\mu = 2m_H$
- This uncertainty in the irreducible background translates into uncertainty in the extraction of the coupling strenghts. To reduce the uncertainty, a differential NLO calculation is needed for the QCD background process $H + 2$ jets

$H + 2$ Jet Production – Event Rates for 1 fb^{-1}

- Event rates for the Hjj WBF signal(NLO) and Hjj background(LO), including our WBF requirement that at least one jet have $1.6 < |\eta| < 4.4$ (no BR included)

p_T cut [GeV]	20	40	80
Signal ($m_H = 115$)	1374	789	166
Bkg	1196	382	92
Purity	0.53	0.67	0.64
Signal ($m_H = 200$)	928	545	121
Bkg	534	179	46
Purity	0.63	0.75	0.72

- Recall $$P = S/(S + B)$$
  - Purity is independent of total integrated luminosity
- p_T cut of 40 GeV yields a good S/B across the range $m_H = 115$–200 GeV. p_T cut of 20 GeV is marginal
- Signal purities of ~ 65% for p_T cut $\gtrsim 40$ GeV; purity is greater at the larger values of m_H

$H + 2$ Jets – Derivation of Coupling Uncertainty

- Both the signal (S) and the background (B) have $H + 2$ jets; $N =$ total number of $H + 2$ jets observed
- Want the uncertainty $\delta g/g$ on the coupling of the Higgs boson to vector bosons
- Define $r = g^2_{\text{observed}}/g^2_{\text{predicted}} \rightarrow r = \frac{(N-B)}{S}$
- Uncertainty in r:

$$\delta r/r = \sqrt{(\delta S/S)^2 + ((\delta N)^2 + (\delta B)^2)/(N - B)^2}$$

- In terms of purity P = S/(S + B)

$$\frac{\delta g}{g} = \frac{1}{2}\sqrt{(\frac{\delta S}{S})^2 + \frac{1}{P^2}(\frac{\delta N}{N})^2 + \frac{(1-P)^2}{P^2}(\frac{\delta B}{B})^2}$$

  - Factor $1/P$ that multiplies $\delta N/N \rightarrow$ $P < 1$ dilutes statistical power of data
  - Factor $(1 - P)/P$ that multiplies $\delta B/B \rightarrow$ $P \rightarrow 1$ reduces role of uncertainty in B
  - Size of background is included in P

Estimates of Uncertainties in S, B, and N

- Let $\delta S/S = 5\%$

  NLO effects are known; μ dep and PDF uncert are estimated

- Let $\delta B/B = 30\%$

  NLO effects not calculated yet for $H + 2$ jets; μ dep of the NLO inclusive process is $\sim 20\%$ for $\frac{1}{2}m_H < \mu < 2m_H$; PDF another $\sim 5\%$

- For N and $\delta N/N$, we must specify decay modes of H
  - for $m_H = 115$ GeV, pick $H \to \tau^+\tau^-$ with one τ decaying to hadrons and one to leptons combined branching ratio 0.033; use hadronic tagging efficiency 0.26; net reduction factor $\epsilon \sim 0.01$
  - for $m_H = 200$ GeV, pick $H \to W^+W^-$; if both decay to leptons, $\epsilon \sim 0.036$

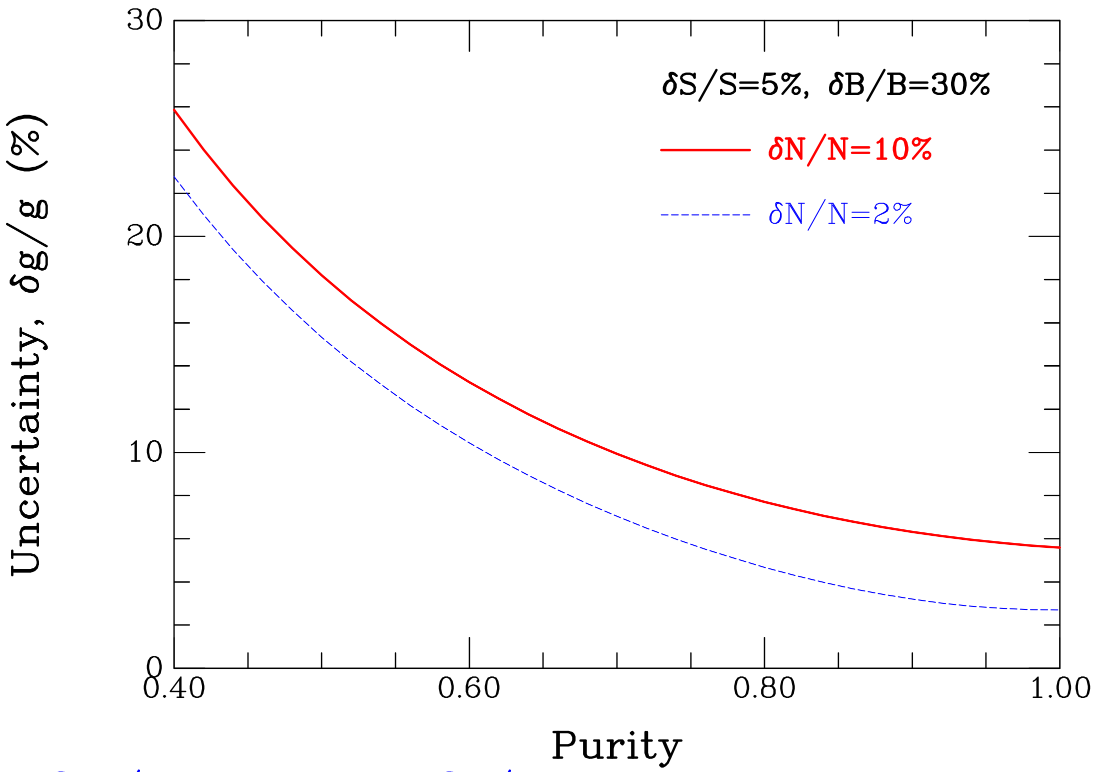
- "Low luminosity" minimum of ~ 10 fb^{-1} integrated luminosity is needed to discover H in the WBF process

  ATLAS, S. Asai et al hep-ph/0402254 one (good) year of LHC operation at 10^{33} cm^{-2}s^{-1}
  - $(S + B) \sim 12000 \times 0.01 = 120$ events at $m_H = 115$ GeV and $p_T^{\rm cut} = 40$ GeV; $\delta N/N \sim 10\%$
  - $(S + B) \sim 7000 \times 0.036 \sim 250$ events at $m_H = 200$ GeV and $p_T^{\rm cut} = 40$ GeV; $\delta N/N \sim 6\%$

Estimates of Uncertainties in S, B, and N

- "High luminosity" after 5 years of LHC operation, anticipate an integrated luminosity of ~ 200 fb^{-1}
  - at $m_H = 115$ GeV and $p_T^{\rm cut} = 40$ GeV;
    $\delta N/N \sim 2$% in the $\tau\tau$ mode
  - at $m_H = 200$ GeV and $p_T^{\rm cut} = 40$ GeV;
    $\delta N/N \sim 1.5$% in the WW mode

Coupling Uncertainty *vs* Signal Purity



- If $\delta N/N \sim 10\%$ $\delta g/g \sim 10\%$ for $P = 0.7$
- If $\delta N/N \sim 2\%$ $\delta g/g \sim 7\%$ for $P = 0.7$
- Uncertainties in S and in B dominate uncertainty in g.
  With $P = 0.7$ and $\delta N/N = 2\%$, then $\delta S/S$ and $\delta B/B$ have to be reduced to 3% and 6% before statistics control the answer
- $P > 0.65$ permits $\delta g/g \sim 10\%$ after 200 fb^{-1}
  Obtained for $p_T^{\rm cut} > 40$ GeV at $m_H = 115$ GeV and for $p_T^{\rm cut} > 20$ GeV at $m_H = 200$ GeV
- Suppose $K^{\rm NLO}_{\rm background} \sim 1.6$
  $P = 0.56$ for $p_T^{\rm cut} > 40$ GeV at $m_H = 115$ GeV $\rightarrow$ $\delta g/g = 13\%$
  $P = 0.52$ for $p_T^{\rm cut} > 20$ GeV at $m_H = 200$ GeV $\rightarrow$ $\delta g/g = 15\%$

Comparisons with LC Estimates of Couplings

- HZZ coupling
  - Higgs-strahlung is the dominant production process, $e^+e^- \to ZH$. Once the Z is identified, H is discovered in the missing mass distribution. The HZZ coupling strength is measured independently of the Higgs boson decay products
- Expected accuracy in $\Delta\sigma_{ZH}/\sigma_{ZH}$
  - For m_H in the range 120 to 160 GeV, Tesla TDR Part III, pp 26-27, quotes an expected statistical accuracy of ± 2.8% (e^+e^- and $\mu^+\mu^-$ channels combined), plus ± 2.5% systematics at $\sqrt{s} = 350$ GeV and 500fb^{-1}
  - ALC Working Group Snowmass 2001 Resource Book, p. 120, lists uncertainty of 6.5% at $m_H = 120$ GeV, and 7% at $m_H = 200$ GeV with $\sqrt{s} = 500$ GeV and 500fb^{-1}
- Expected accuracy in $\delta g_{ZZH}/g_{ZZH} \simeq 3$%

LC Estimates (continued)

- HWW coupling
  - Measurement of the HWW coupling is necessary to test the $SU(2)$ relationship between HWW and HZZ.
- The usual method relies on the WBF process $e^+e^- \to \nu\bar{\nu}H$, plus knowledge of at least one H branching fraction. Signals and backgrounds for $H \to b\bar{b}$ are studied in detail in Desch and Meyer, LC-PHSM-2001-25 and Brau, Potter, Iwasaki, Snowmass 2001
- Expected accuracy in $\Delta\sigma_{\nu\bar{\nu}H}/\sigma_{\nu\bar{\nu}H}$
  - In the context of the SM, after expected uncertainties on the $BR(H \to b\bar{b})$ are included, accuracies of 2.8% to 13% can be obtained for m_H in the range 120 GeV to 160 GeV at $\sqrt{s} = 500$ GeV and 500fb^{-1}
- Expected accuracy in $\delta g_{WWH}/g_{WWH} \simeq 3$% to $\simeq 7$%
- Knowledge of HWW coupling strength along with m_H allows one to compute the partial width Γ_W. If an independent measurement of $\mathrm{BR}(H \to WW^*)$ is also available, the Higgs boson total width Γ_H is obtained: $\Gamma_H = \Gamma_W/\mathrm{BR}(H \to WW^*)$

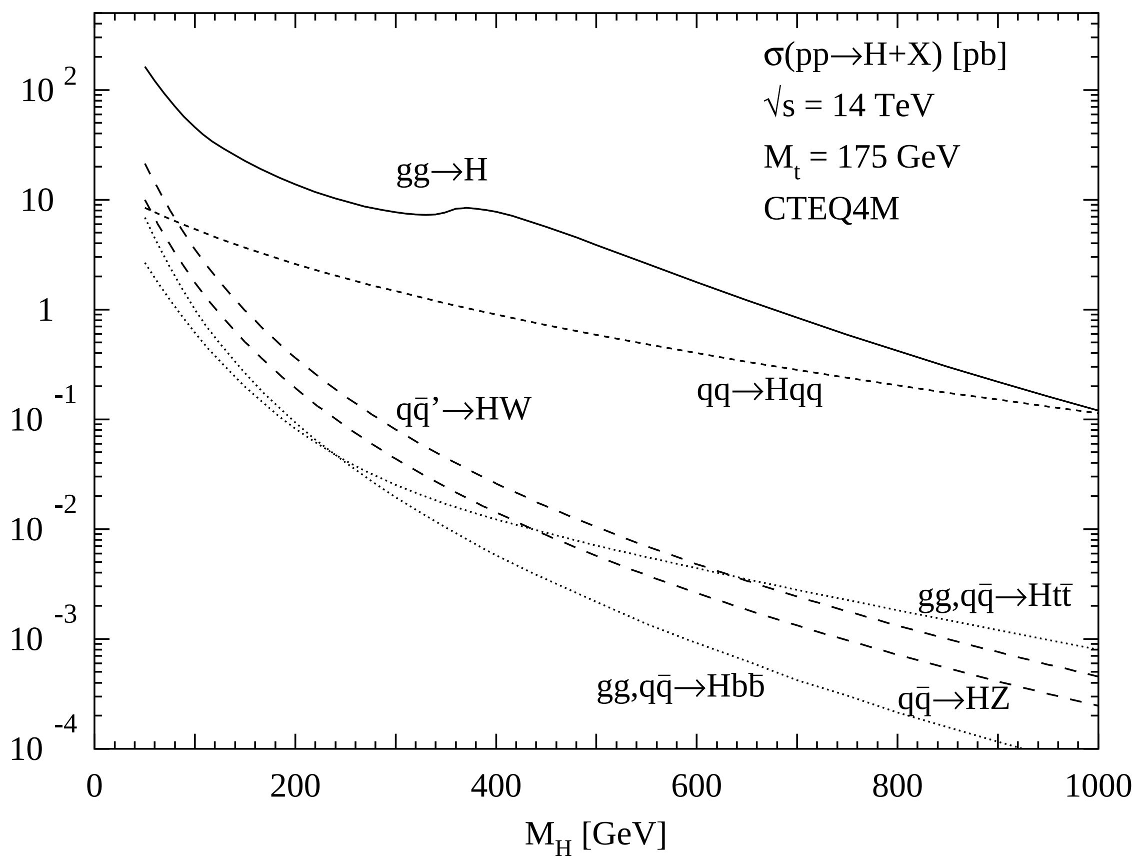
Summary

- Studied $H + 2$ jet production at the energy of the LHC. Fully differential hard matrix elements used to generate p_T spectra
- Investigated effectiveness of prescriptions to separate/enhance the WBF signal with respect to the *irreducible* QCD background
- Evaluated the signal purity P (fraction of real H events produced by WBF) in each case as a function of the transverse momentum cut used to define the tagging jets
- After 200 fb^{-1} are accumulated at the LHC, it may be possible to achieve an accuracy $\delta g/g \sim 10\%$ in the effective coupling (combination of HWW and HZZ) of the Higgs boson to weak bosons. (These estimates are less optimistic than those in the Les Houches 2003 study)
- With a 500 GeV LC and 500fb^{-1}, the expected accuracies are $\delta g_{ZZH}/g_{ZZH} \simeq 3\%$ for $120 < m_H < 200$ GeV and $\delta g_{WWH}/g_{WWH} \simeq 3\%$ to $\simeq 7\%$ for $120 < m_H < 160$ GeV

1. Introduction and Motivation

- The Higgs boson is expected to be produced at the LHC through various partonic production processes and observed in its decays to SM particles
  - $gg \to hX$, with $h \to \gamma\gamma$, $h \to WW^*$, ZZ^* ;
  - $gg \to t\bar{t}hX$, with $h \to b\bar{b}$ or $h \to \gamma\gamma$;
  - $qq \to hqqX$ via $W^+W^-(ZZ) \to hX$, with $h \to WW^*$, $h \to \gamma\gamma$, or $h \to \tau^+\tau^-$
- The fully inclusive gluon-gluon fusion subprocess $gg \to hX$ is the dominant production mechanism; $qq \to H + 2$ jets is next in line

(figure from M. Spira)

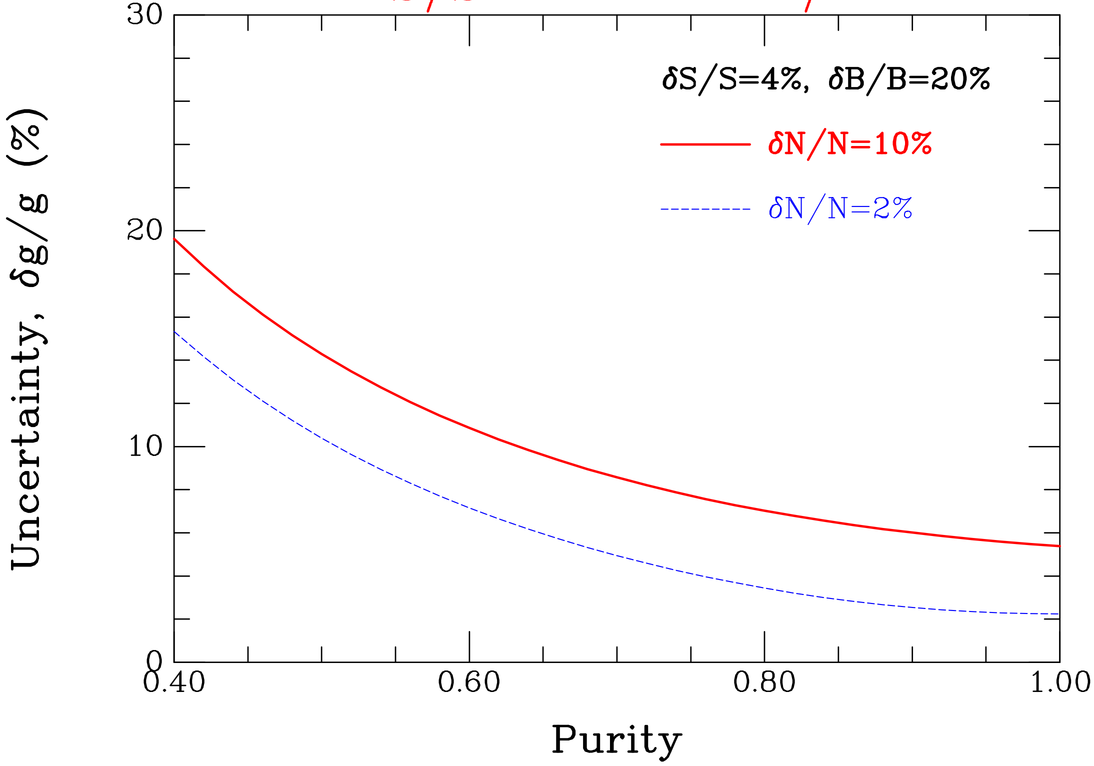


Generic Cuts

- Generic cuts Figy et al. Jets from the Monte Carlo runs are clustered according to the k_T algorithm with
  - $p_T^{\mathrm{jet}} > 20$ GeV, to be raised
  - jet pseudo-rapidity $|\eta^{\mathrm{jet}}| < 4.5$, and
  - jet separation $\Delta R_{jj} = \sqrt{\Delta\eta_{jj}^2 + \Delta\phi_{jj}^2} > 0.8$
- The two jets with the highest p_T are chosen as the tagging jets and ordered in rapidity, $\eta_{j_1} < \eta_{j_2}$
- To approximate the acceptance for the Higgs boson decay products imagine a Higgs boson decay to two charged particles, denoted "leptons"
  - Require $p_T^{\mathrm{lept}} > 20\ \mathrm{GeV}$, $|\eta^{\mathrm{lept}}| < 2.5$, $\Delta R_{j\ell} > 0.6, \eta_{j_1} < \eta_{\mathrm{lept}} < \eta_{j_2}$
- Higgs decay products lie between the tagging jets

Coupling Uncertainty *vs* Signal Purity

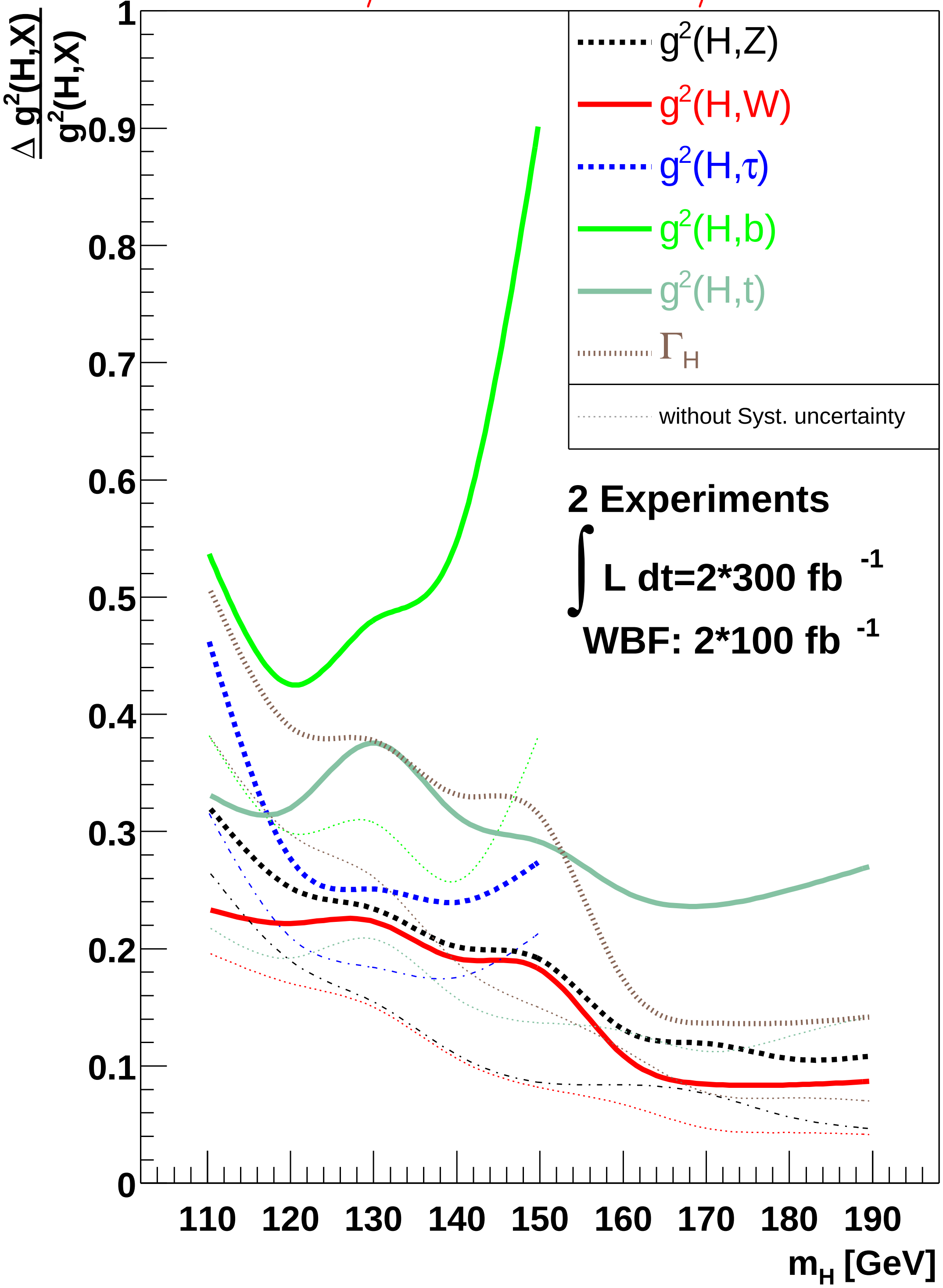
- Smaller values of $\delta S/S = 4\%$ and $\delta B/B = 20\%$



- If $\delta N/N \sim 10\%$ $\quad \delta g/g \sim 9\%$ $\quad$ for $P = 0.7$
- If $\delta N/N \sim 2\%$ $\quad \delta g/g \sim 5\%$ $\quad$ for $P = 0.7$
- New lower values of $\delta g/g$ are very similar to Düehrssen et al, Les Houches 2003 for comparable luminosity
- Not evident from these figures that there is much to gain from $P > 0.7$

Coupling Uncertainty vs Les Houches Results

- Smaller values of $\delta S/S = 4\%$ and $\delta B/B = 20\%$



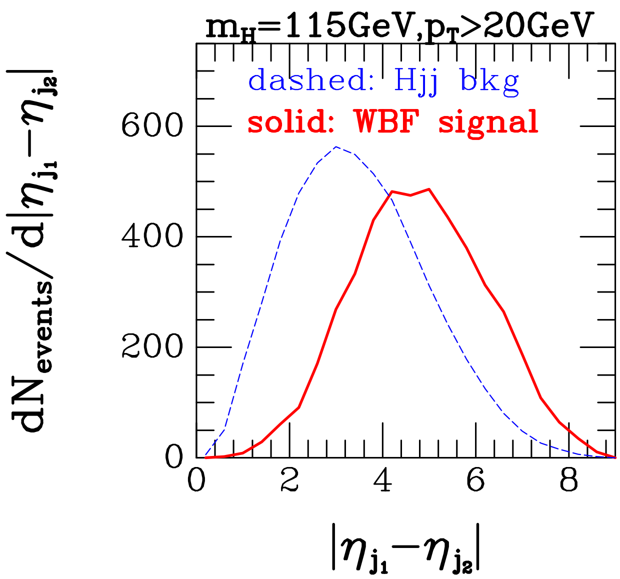
- Scope of the Les Houches study is more ambitious, but the WBF results at high luminosity are quite similar

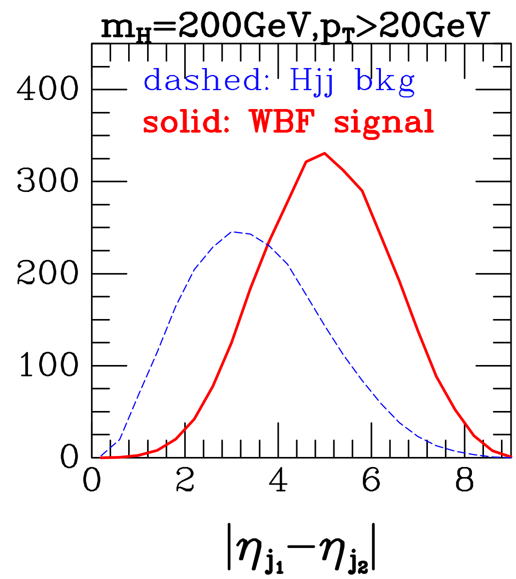
4. Alternative WBF Prescriptions

- We use the requirement that at least one jet have $1.6 < |\eta| < 4.4$
- A different prescription requires instead a rapidity separation requirement $|\eta_{j1} - \eta_{j2}| > 4$
- Another requires an invariant mass cut $M_{jj} > 800$ GeV
  $\rightarrow$ Figures and Tables
- With these alternatives, there is a significant gain in P for $p_T^{\rm cut} = 20$ GeV, but not for larger values. The gain is accompanied by loss in signal rate at all p_T
- Potential advantages of simple cut on $|\eta|$ of one jet in a high luminosity environment
  - In data (and at higher orders in QCD) there are several jets; our prescription may be easier to implement
  - In a high luminosity environment, with more than one event per beam crossing, selection on only one jet (plus the H) reduces chance that jets from different events are used
- Full experimental simulation would be useful. One could begin with hard QCD LO $H + 2$ jet matrix elements plus Pythia showering – improvement over current ATLAS studies (c.f., S. Asai et al hep-ph/0402254)

$H + 2$ Jet Production – Jet Rapidity Separation

- Higgs boson H production via WW scattering in NLO and via gg QCD processes (LO) (for 1 fb^{-1})





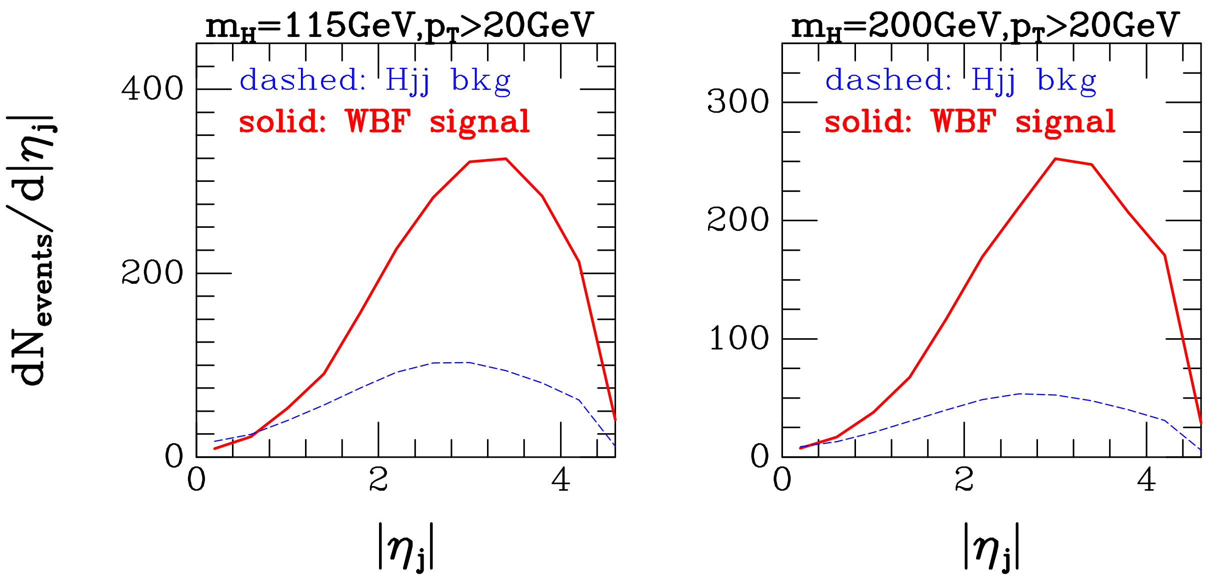
- Shape motivates a rapidity separation cut

$$|\eta_{j1} - \eta_{j2}| > 4$$

p_T cut [GeV]	20	40	80
Signal ($m_H = 115$)	1297	718	137
Bkg	758	207	38
Purity	0.63	0.78	0.78
Signal ($m_H = 200$)	911	521	106
Bkg	349	102	20
Purity	0.72	0.84	0.84

$H + 2$ Jet Production – Jet Rapidity with Mass Cut

- Higgs boson H production via WW scattering in NLO and via gg QCD processes (LO) (for 1 fb^{-1})



- Alternative WBF prescription:

$$M_{jj} > 800GeV$$

p_T cut [GeV]	20	40	80
Signal ($m_H = 115$)	808	561	158
Bkg	304	183	82
Purity	0.73	0.75	0.66
Signal ($m_H = 200$)	617	428	121
Bkg	157	95	43
Purity	0.80	0.82	0.74